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of

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for

PLASMA MASS FILTER WITH INDUCTIVE ROTATIONAL DRIVE

FIELD OF THE INVENTION

The present invention pertains generally to devices and methods for separating the constituents of a multi-constituent material. More particularly, the present invention pertains to devices for efficiently rotating a plasma that is created from a multi-constituent material to separate particles in the plasma according to their respective mass to charge ratios. The present invention is particularly, but not exclusively, useful as a filter to separate high mass particles from low mass particles in a plasma that is rotated using a rotating magnetic field.

BACKGROUND OF THE INVENTION

There are many applications in which it is desirable to separate the constituents of a multi-constituent material. One such application is the treatment of waste that is hazardous due to the presence of one or more highly radioactive materials. For example, it is well known that only a small percentage of the entire volume of waste from a commercial nuclear reactor consists of radionuclides that cause the waste to be hazardous. Thus, if these radionuclides can somehow be segregated from the other constituents of the nuclear waste, the handling and disposal of the relatively small volume of hazardous components can be greatly simplified and the overall cost of nuclear waste disposal can be significantly reduced.

One separation technique that has previously been suggested takes advantage of the fact that the orbital motions of charged particles (ions) in crossed electric and magnetic fields, will differ from each other according to their respective mass to charge ratio. Thus, when the probability of ion collision is significantly reduced, the possibility for improved separation of the particles due to their orbital mechanics is increased. For example, U.S. Patent No. 6,096,220, which issued on August 1, 2000 to Ohkawa, for an invention entitled "Plasma Mass Filter" and which is assigned to the same

assignee as the present invention, discloses a device which relies on the different, predictable, orbital motions of charged particles in crossed electric and magnetic fields in a chamber to separate the charged particles from each other. In the filter disclosed in Ohkawa '220, the magnetic field is oriented substantially axially, and an electric field is applied that is oriented substantially radially and outwardly from the axis, with both the magnetic field and the electric field being substantially uniform both azimuthally and axially.

As further disclosed in Ohkawa '220, this configuration of applied electric and magnetic fields causes ions having relatively low mass to charge ratios to be confined inside the chamber during their transit of the chamber. On the other hand, ions having relatively high mass to charge ratios are not so confined. Instead, these larger mass ions are collected at the wall of the chamber before completing their transit through the chamber. The demarcation between high mass particles and low mass particles is a cut-off mass, M_c, which is established by setting the magnitude of the magnetic field strength, B, the positive voltage along the longitudinal axis, V_{ctr}, and the radius of the cylindrical chamber, "a". The cut-off mass, M_c, can then be determined with the expression:

$$M_c = ea^2(B)^2 / 8V_{ctr}$$

One important performance metric for a separation device such as the one disclosed in Ohkawa '220 is the amount of energy that is required to obtain a desired level of separation. In greater detail, energy must be expended to convert the multi-constituent material into a plasma, including energy to vaporize, ionize and heat the multi-constituent material, and in addition, energy must be expended to rotate the ions in the plasma. In the device disclosed in Ohkawa '220, plasma rotation is driven by a radial current that is established in the uniform axial magnetic field (i.e. the configuration is similar to a homopolar motor). Thus, the plasma rotates in response to applied electric and magnetic fields (j_r x B_z). More specifically, the applied electric field is generated using energized, direct-current (DC) electrodes that are placed in contact with the plasma. The drawbacks associated with these active DC electrodes are two-fold. The first drawback, as implied above,

involves energy considerations. Specifically, it would be desirable if a more energy efficient mechanism was available to rotate the plasma. In addition, the use of active DC electrodes that are in contact with the plasma can result in undesirable DC arcing.

The present invention contemplates a plasma rotation that is driven inductively by a rotating magnetic field similar to the field used to rotate the rotor of an induction motor. An additional uniform axial magnetic field is applied, the effect of which is two-fold. First, in the applied axial magnetic field, the rotating plasma acts as a homopolar generator driven by an induction motor. The result is an induced electric field that is oriented radially. In addition, the applied axial magnetic field interacts with the induced radial electric field to separate relatively high mass ions from relatively low mass ions in a manner similar to the device disclosed in Ohkawa '220.

The characteristics of a system in which plasma rotation is driven inductively can be estimated by considering a simplified model in which the plasma is replaced by a conductive cylinder. For the model, the conductive cylinder is supported by an axle and multiple concentric slip rings are positioned at both ends of the cylinder and electrically connected to the cylinder. The cylinder is further disposed within a coil system that produces a rotating magnetic field represented by the vector potential $A_z \propto \exp[i\, l\, \theta - i\, \omega\, t]$.

The field components are given by:

$$B_r = [\, i\, l / r\,]\, A_z \qquad [1a]$$

$$B_\theta = -\partial A_z / \partial r \qquad [1b]$$

$$E_z = i\, \omega\, A_z \qquad [1c]$$

Using Ohm's law, the expression:

$$E_z - \omega_0\, r\, B_r = \sigma^{-1}\, j_z \qquad [2]$$

can be obtained, where ω_0 is the angular frequency of the cylinder rotation and σ is the electrical conductivity of the cylinder.

The combination of Maxwell's equations and Ohm's law yields:

$$\{\, r^{-1}\, \partial / \partial r\, [\, r\, \partial / \partial r] - l^2 / r^2 + i\, \mu_0\, \sigma\, [\, \omega - l\, \omega_0\,]\, \}\, A_z = 0 \qquad [3]$$

The solution of equation [3] is given by:

$$A_z = A J_l [k r] \exp[i l \theta - i \omega t] \quad [4]$$

where

$$k^2 = i \mu_0 \sigma \omega' \quad [5a]$$

$$\omega' = \omega - l \omega_0 \quad [5b]$$

Thus, the skin depth k^{-1} depends on the relative rotational frequency between the cylinder and the field. The time averaged force per unit volume, F, is given by:

$$F_\theta = [\tfrac{1}{2}] j_z^* B_r = [\sigma \omega' l / 2 r] A^*A J_l[k^*r] J_l[kr] \quad [6]$$

In terms of the magnetic field strength, equation [6] becomes:

$$F_\theta = [\mu_0 \sigma \omega' r / l] [B_r^* B_r / 2 \mu_0] \quad [7]$$

Thus, the force has the characteristics of an induction motor in that the force is small at $\omega_0 \sim 0$ (because the field does not penetrate) and also the force is small when $\omega' \sim 0$.

Continuing with the model, the current flows in the axial direction in the conductive cylinder and in the azimuthal direction in the slip rings. The contact resistance between the cylinder and the slip rings is present in the electrical circuit and therefore should be included in the conductivity of the above formula. When the cylinder is replaced with a plasma, the contact resistance is replaced by the resistance across the sheath and the equivalent conductivity σ^* is given by:

$$\sigma^* = \sigma \{1 + [\sigma k_B T_e / e^2 n v_s L]\}^{-1} \quad [8]$$

where $e\, n\, v_s$ is the ion saturation current and L is the half length of the plasma. At low densities (i.e. $n < 10^{19}\ m^{-3}$) the sheath resistance dominates.

During steady state rotation, the inductive drive balances the friction of the rotating conductive cylinder. In the rotating plasma, the loss of the rotating ions at the ends represents the frictional loss. For the device disclosed in Ohkawa '220, the frictional loss is balanced by the homopolar drive, $j_r B_z$, given by:

$$j_r B_z = n M v_s \omega_0 r / L \quad [9]$$

where M is the ion mass. If the inductive drive (given by eq [6]) is to have the same radial distribution as the homopolar drive (given by eq [9]), the

azimuthal mode number l should be unity for kr<<1 and uniform density. By putting l = 1 and equating eq [7] and eq [9] the following expression can be obtained:

$$\sigma^* \omega' |B_r|^2 / 2 = n M v_s \omega_0 / L \qquad [10]$$

It is noted that B_r is approximately uniform. At low densities $\sigma^* << \sigma$ the following expression can be obtained:

$$|B_r|^2 = [2 M k_B T_e / e^2 L^2] [\omega_0 / \omega'] \qquad [11]$$

Thus, the required field strength is independent of the plasma density. Accordingly, the power required to inductively drive the rotation is approximately equal to the active electrode DC supply power for the device disclosed by Ohkawa '220 operating at a field of about 10^{-3} T.

In light of the above, it is an object of the present invention to provide devices and methods suitable for the purposes of separating the constituents of a multi-constituent material. It is another object of the present invention to provide devices and methods for efficiently rotating a plasma that is created from a multi-constituent material to separate particles in the plasma according to their respective mass to charge ratios. It is yet another object of the present invention to provide devices and methods for efficiently rotating a plasma and separating the plasma in crossed electric and magnetic fields without using active electrodes that can create undesirable DC arcing. Yet another object of the present invention is to provide devices and methods for rotating a plasma to separate particles in the plasma according to their respective mass to charge ratios which are easy to use, relatively simple to implement, and comparatively cost effective.

SUMMARY OF THE INVENTION

The present invention is directed to devices and methods for separating the constituents of a multi-constituent material. In overview, the multi-constituent material is first converted into a multi-species plasma having particles with relatively high mass to charge ratios (M_1) and particles with relatively low mass to charge ratios (M_2). The multi-species plasma is then

rotated using a rotating magnetic field. During plasma rotation, an induced radially oriented electric field combines with an applied axially aligned magnetic field to separate the high mass particles (M_1) from the low mass particles (M_2).

In greater structural detail, the separating device typically includes an elongated, cylindrical shaped wall that extends from a first open end to a second open end, surrounds a chamber therebetween, and defines a longitudinal axis. The device further includes a plurality of substantially rectangular shaped coils that are mounted on the outside of the wall to establish a magnetic field throughout the chamber. Each rectangular shaped coil has a pair of opposed sides that are substantially straight and oriented substantially longitudinally when the coil is mounted on the wall. In addition, each rectangular shaped coil has a pair of opposed sides that are curved to conform to the radial contour of the cylindrical wall. As a consequence, these curved sides are oriented substantially azimuthally relative to the longitudinal axis when the coil is mounted on the wall.

A source of multi-phase, alternating current is provided to energize the rectangular shaped coils and produce the magnetic field in the chamber. For instance, in one embodiment, four rectangular shaped coils are uniformly distributed around the circumference of the wall, with each coil extending substantially from the first end to the second end of the wall. In this embodiment, each coil receives an alternating current having an angular frequency, ω, from the multi-phase source with the current phase in each rectangular shaped coil being shifted by approximately ninety degrees (90°) from coil to coil around the cylinder. With this cooperation of structure, a magnetic field, B_0, is established in the chamber that is aligned substantially perpendicular to the axis and which rotates about the axis due to the phasing of the current in the rectangular shaped coils.

The device further includes one or more coils, which are typically circularly shaped. When energized, these circularly shaped coils produce an axially aligned magnetic field, B_z, in the chamber that is constant in time. Also for the present invention, the device includes a first plurality of ring-shaped

electrodes that are concentrically arranged about the longitudinal axis and attached to the first end of the wall. A second plurality of concentrically arranged, ring-shaped electrodes is attached to the second end of the wall. Each electrode is connected to an electrical ground through a relatively large resistor.

In operation, the rotating magnetic field, B_0, causes currents within the plasma to flow longitudinally and enter the passive electrodes where the currents then flow azimuthally. From the electrodes, the current flows through the resistors and then to ground. The lorentz force due to the longitudinally oriented currents and the magnetic field, B_0, accelerates the plasma in the azimuthal direction. In the presence of the axially aligned magnetic field, B_z, the rotating plasma induces a radially oriented electric field, E_r, in the chamber. The relatively large resistors allow the electric field, E_r, to 'charge up' in the chamber.

In the crossed electric and magnetic fields (i.e. $E_r \times B_z$), ions in the plasma having a relatively low mass to charge ratio (M_2) are placed on relatively small radius orbital trajectories and transit through the chamber exiting at one of the chamber ends. On the other hand, ions in the plasma having a relatively high mass to charge ratio (M_1) are not so confined. Instead, these larger mass ions are placed on relatively large radius trajectories and strike the cylindrical wall where they are captured. Specifically, for a cylindrical wall having an inside radius "a" from the longitudinal axis, ions having a mass (M_1) that is greater than a cut-off mass, M_c ($M_1 > M_c$) will be collected at the wall, where

$$M_c = eB_z / 4\omega$$

wherein "e" is the ion charge.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features of this invention, as well as the invention itself, both as to its structure and its operation, will be best understood from the accompanying drawings, taken in conjunction with the accompanying

description, in which similar reference characters refer to similar parts, and in which:

Fig. 1 is a simplified, perspective view of a plasma mass filter having an inductive rotational drive with portions of the filter broken away for clarity;

Fig. 2 is a cross-sectional view of the plasma mass filter shown in Fig. 1 as seen along line 2-2 in Fig. 1; and

Fig. 3 is a cross-sectional view of the plasma mass filter as in Fig. 2 showing the rotating magnetic field (note: electrodes and coils are not shown in Fig. 3 for clarity).

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring initially to Fig. 1, a plasma mass filter is shown and generally designated 10. As shown, the filter 10 includes a substantially cylindrical shaped wall 12 which surrounds a chamber 14, and defines a longitudinal axis 16. The actual dimensions of the chamber 14 are somewhat, but not entirely, a matter of design choice. However, the radial distance "a" (shown in Fig. 2) between the longitudinal axis 16 and the wall 12 is a parameter which will affect the operation of the filter 10, and as indicated elsewhere herein, must be taken into account.

With cross-reference now to Figs. 1 and 2, it can be seen that the filter 10 further includes four substantially rectangular shaped coils 18a-d that are mounted on the outside of the wall 12 to establish a magnetic field throughout the chamber 14. As further shown for the filter 10, each rectangular shaped coil 18a-d has a pair of opposed sides 20a,b that are substantially straight and oriented substantially longitudinally when the coils 18a-d are mounted on the wall 12. In addition, each rectangular shaped coil 18a-d has a pair of opposed sides 22a,b that are curved to conform to the radial contour of the cylindrical wall 12. As a consequence, the curved sides 22a,b are oriented substantially azimuthally relative to the longitudinal axis 16 when the coils 18a-d are mounted on the wall 12.

Fig. 1 further shows that the filter 10 includes a source 24 of multi-phase, alternating current having an angular frequency, ω, to energize each coil 18a-d and produce a magnetic field in the chamber 14. Typically, each coil 18a-d receives an alternating current from the multi-phase source 24 having a current phase that is shifted by approximately ninety degrees (90°) from coil 18a-d to coil 18a-d around the cylindrical wall 12. In greater detail, the current phase in coil 18b is shifted by approximately ninety degrees relative to coil 18a. Also, the current phase in coil 18c is shifted by approximately ninety degrees relative to coil 18b and by approximately one-hundred-eighty degrees relative to coil 18a. Furthermore, the current phase in coil 18d is shifted by approximately ninety degrees relative to coil 18c and by approximately two-hundred-seventy degrees relative to coil 18a. With this cooperation of structure, a magnetic field, B_0 is established in the chamber 14 that is aligned substantially perpendicular to the axis 16 and which rotates about the axis 16, as shown in Fig. 3. More specifically, Fig. 3 shows the magnetic field B_0, in a first orientation (represented by three solid field lines) and after a rotation about the axis 16 to a second orientation (represented by three dotted field lines).

As shown in Fig. 1, the filter 10 includes circularly shaped coils 25a,b which are mounted on the outer surface of the wall 12 to surround the chamber 14. In a manner well known in the pertinent art, the coils 25a,b can be activated to create a magnetic field in the chamber 14 which has a component, B_z that is substantially constant in time and is directed substantially along the longitudinal axis 16.

Cross-referencing Figs. 1 and 2, it can be seen that the filter 10 includes three ring-shaped electrodes 26a-c that are concentrically arranged about the longitudinal axis 16 and attached to the first end 28 of the wall 12. As best seen in Fig. 2, another set of three concentrically arranged, ring-shaped electrodes 30a-c is attached to the second end 32 of the wall 12. It is to be further appreciated from Fig. 1 that each electrode 26a-c, 30a-c is connected to a relatively large resistor in resistor bank 34 via wires 36, 38.

From resistor bank 34, each resistor is connected to an electrical ground 40 via wire 42.

Continuing with Fig. 1, it can be seen that the filter 10 includes an injector 44 that is positioned at the end 32 of the wall 12. Functionally, the injector 44 first converts a multi-constituent material into a multi-species plasma 46 and injects the multi-species plasma 46 into the chamber 14. As shown in Fig. 1, the multi-species plasma 46 typically includes particles with relatively high mass to charge ratios, M_1, (hereinafter high mass particles 48) and particles with relatively low mass to charge ratios, M_2, (hereinafter low mass particles 50). For instance, an inductively coupled plasma (ICP) torch can be used, or any other injector known in the pertinent art capable of converting a multi-constituent material into a multi-species plasma 46 and injecting the multi-species plasma 46 into the chamber 14, can be used in the filter 10.

In operation, the rotating magnetic field, B_0 causes electrical currents, J, within the plasma to flow longitudinally through the chamber 14 and enter the passive electrodes 26a-c, 30a-c where the electrical currents then flow azimuthally. From the electrodes 26a-c, 30a-c, the current flows through resistors in the resistor bank 34 and then to ground 40. The lorentz force due to the longitudinally oriented currents, J, and the magnetic field, B_0 causes the plasma (including the high mass particles 48 and low mass particles 50) to rotate about the axis 16. In the presence of the axially aligned magnetic field, B_z, the rotating particles 48, 50 induce a radially oriented electric field, E_r, (see Fig. 2) in the chamber 14.

Under the influence of the crossed electric and magnetic fields (i.e. $E_r \times B_z$), charged particles 48, 50 in the plasma 46 will travel generally along helical paths around the longitudinal axis 16 similar to the path 52 shown in Fig. 1. Due to the configuration of the electric field, E_r, and magnetic field, B_z, the plasma mass filter 10 causes charged particles 48, 50 in the multi-species plasma 46 to behave differently as they travel in the chamber 14. Specifically, charged particles having masses above a cutoff mass, M_c, given by the equation:

$M_c = eB_z / 4\omega$

are not able to transit the chamber 14 and, instead, they are ejected into the wall 12. In the above expression for the cutoff mass, M_c, the variables B_Z and ω can be specifically designed or established for the operation of plasma mass filter 10. Accordingly, charged high-mass particles 48 of mass M_1, where $M_1 > M_c$, will be placed on relatively large radius trajectories where they will strike and be captured by the wall 12 of the filter 10. On the other hand, charged low-mass particles 50 with mass M_2, where $M_2 < M_c$, will be placed on relatively large radius trajectories (i.e. orbits). These low-mass particles 50 are confined in the chamber 14 during their transit through the chamber 14. Consequently, the low-mass particles 50 exit the chamber 14 and are, thereby, effectively separated from the high-mass particles 50.

The relatively large resistors allow the electric field, E_r, to 'charge up' in the chamber 14 to a desired level to effect separation as described above. The electrodes 26a-c, 30a-c are grounded to drain current associated with the captured high mass ions 50.

While the particular Inductive Rotational Drive as herein shown and disclosed in detail is fully capable of obtaining the objects and providing the advantages herein before stated, it is to be understood that it is merely illustrative of the presently preferred embodiments of the invention and that no limitations are intended to the details of construction or design herein shown other than as described in the appended claims.